Top-level summary of experimental discussions:

Identified important remaining anomalies for NIF potentially caused by kinetic physics:

- *Hohlraum*: Low-mode drive asymmetry, "Oggie multipliers"
- *Fuel*: observed ρR (DSR) lower than sims; observed <Ti> higher than sims; <Ti> ratio from different species hard to explain; (Yield ratio from different species?); source of atomic mix

Identified component areas likely to be influenced or dominated by kinetic physics:

- *LEH*: LPI and time-dependent, spatially-dependent hot-electron production
- *Hohlraum*: Au bubble formation, interpenetration of ablator/gas/Au bubble, large magnetic fields, presence of hydro instability growth
- *Ablator*: mix at ablator/DT interface, melting-timescale physics at shock breakout
- *Shock Physics & Fuel Assembly:* "multi-fluid" behavior incl. species separation (many, but not all, indicate little impact in N_K << 0.01 main fuel), multi-Ti, frictional heating; shock-front structure (intrinsically non-hydro); collisionless imprint during shock phase; electric/magnetic fields in hotspot.

Proposed top-level outcomes of the workshop:

- Assemble and grow database of validation data from experiments in hydro & kinetic regimes
- Assemble and grow database of simulation verification problems for hydro & kinetic regimes
- Define the path and timeline to test ICF implosion in existing kinetic-capable codes
- Pursue experiments of *fundamental tests* and *integrated scaling studies* of kinetic physics:
  - See proposed experiments attached

Kinetic Physics in ICF Workshop: Discussion session – Day 3 – Wrap-up

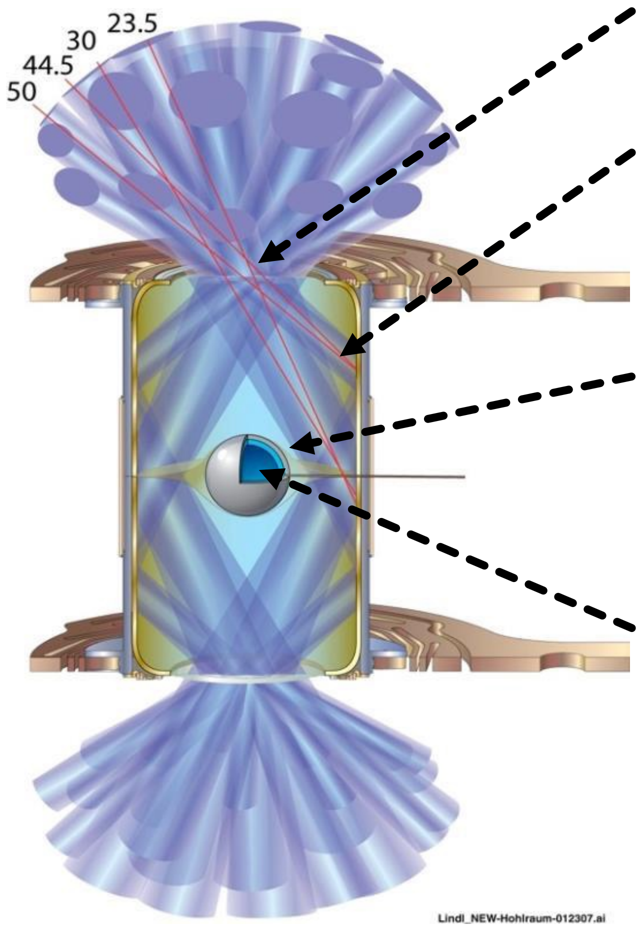
Findings from Experimental discussions

H.G. Rinderknecht
Thursday, April 7, 3:35 pm
481 R2004/2005

LLNL-PRES-692828
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Day 1 Summary: Important anomalies, and component areas with "kinetic-likely" physics, were identified



LEH/laser transport:
- LPI and time-dependent, spatially-dependent hot-electron production [Afeyan]

Hohlraums:
Outstanding issues: Low-mode drive asymmetry; Oggie multipliers;
- Au bubble formation and evolution (thermodiffusion)
- Plasma interpenetration in ablator/gas/Au bubble region [LePape, Kemp]
- Impact of large electric/magnetic fields on hohlraum performance [Li]

Ablator:
- Species separation in ablated plasma [Ross]
- mix at ablator/DT interface (proton/ion transport into ice) [Fernandez, Murillo, Bellei]
- melting-timescale physics at shock breakout [Orth]

Shock Physics & Fuel Assembly:
Outstanding issues: higher-than-observed ρR (DSR), and lower-than-observed <Ti>, in simulations
- Ion species separation and/or "multi-fluid" (dominant for $N_K > 0.01$ [Rosenberg, Herrmann, Hsu, Casey, Schmitt]; for $N_K < 0.01$, data & sims "no" [Casey, Ho] but some sims "yes" [Larroche]) [also Sio, Le, Bellei]
- Multi-species + fields shock-front structure (inherently non-hydro) [Sio, Hua, Hoffman, Le, Taitano]
- Impact of collisionless behavior during shock phase (energy/entropy distribution, initial conditions for deceleration) [Rinderknecht]
- Impact of electric/magnetic fields in hotspot [Li, Hua]

Steve Haan highlighted "Top 10" regions for kinetic physics. For the whitepaper, we should flesh this out

Phenomenon	Will affect	Importance	Experiment strategy, difficulty	Theory/simulation strategy, difficulty	Timescale
LPI	Hot e-, preheat	High	Image surrogate hi-Z cap (underway, NIF)		
Multispecies/ multifluid diffusion	Au bubble	High			
	Ablator	Unknown/low			
	Ablator/DT interface	Medium	Diffusion at isochorically heated interface	Shock break-out test, multifluid, PIC, VFP, …	
	Fuel separation	Medium/Low?	Moderate N_K implosions	Compare VFP and diffusive hydro	<1 yr (expt)
Interpenetration	Ablator/gas/Au collision region	High	TS of interpenetrating flows (underway, OMEGA); dot spectroscopy (underway, NIF)		
Multispecies/ multifluid equilibration	Burn	Medium	High N_K implosions		<1 yr (expt)
Shock structure	Entropy of fuel, entropy of hotspot	Unknown	Thomson scattering in 1D shock-tube (underway, OMEGA); multi-species burn history (underway, OMEGA)	Fokker-Planck; PIC	~1—2 yr
Knudsen layer	Burn, yield, Ti	High			
…					

Day 1 Summary: Proposed outcomes from the workshop

- **Assemble and grow database of validation data from experimental results (publish?)**
  - Define “unit physics” experiments that contribute to meaningful basic physics validation - including kinetic AND fluid regimes, expts on NIF (working group?)
  - Topics: hydrodynamics; multi-species; long mean-free-paths; LPI; shock structure; interface evolution; fusion; …
  - Support “hierarchical validation”: unit physics experiments from hydrodynamic up to kinetic regimes
  - Define best practices for comparison to experimental data

- **Assemble and grow database of verification studies for different codes (publish?)**
  - Topics: analytical hydrodynamics: shocks, Guderley, …; equilibration; binary diffusion at interface (D/Al); imposed B-field, …

- **Define the path to test ICF implosion in kinetic codes**
  - Capability timeline for existing tools: LSP PIC, Ares, Hydro + ZPKZ, FP, …
  - Define verification and validation process, including timeline for “preliminary” (~1yr) and “complete” (~3yr) simulation study.

Day 1 Summary: Proposed experimental research efforts

Fundamental Physics (theory/code verification):

- Detailed nuclear/x-ray burn-history record in implosions (Frenje)
- Scaling of implosion performance with density, composition in DT-filled exploding pushers (Petrasso)
- Diffusion at isochorically heated interface (Fernandez)
- Ion species separation in implosions using spectroscopy (Hsu)
- Shock front structure diagnosis with TS, radiography (Rinderknecht, Ping)
- Interpenetration studies with TS (LePape, Divol)
- …

Integrated Scaling Studies:

- Proton radiography of magnetic fields in NIF-scale hohlraums (Li)
- LPI hot electrons from HF pulse with time/space resolution (Afeyan, Dewald)
- “Wetted foam” platform for hotspot kinetic physics (Olson, LANL)
- “DT Gigabar” platform for hotspot formation dynamics (Rygg, Ping)
- “Dot spectroscopy” for temperature, heat capacity, conditions of central gas (Barrios)
- *Hohlraum performance scaling with gas-fill density: LPI & kinetic physics?*
- *Consistency between hot electrons and backscattered light?*
- …

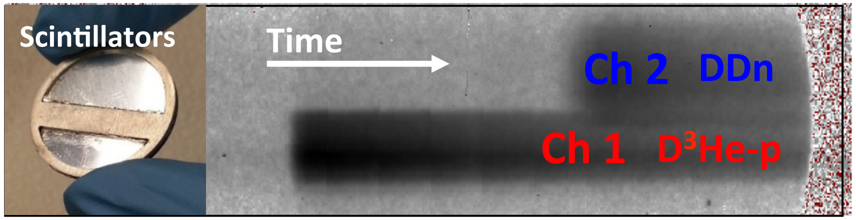
Collaboration is encouraged, esp. on diagnostics to constrain experiments as much as possible

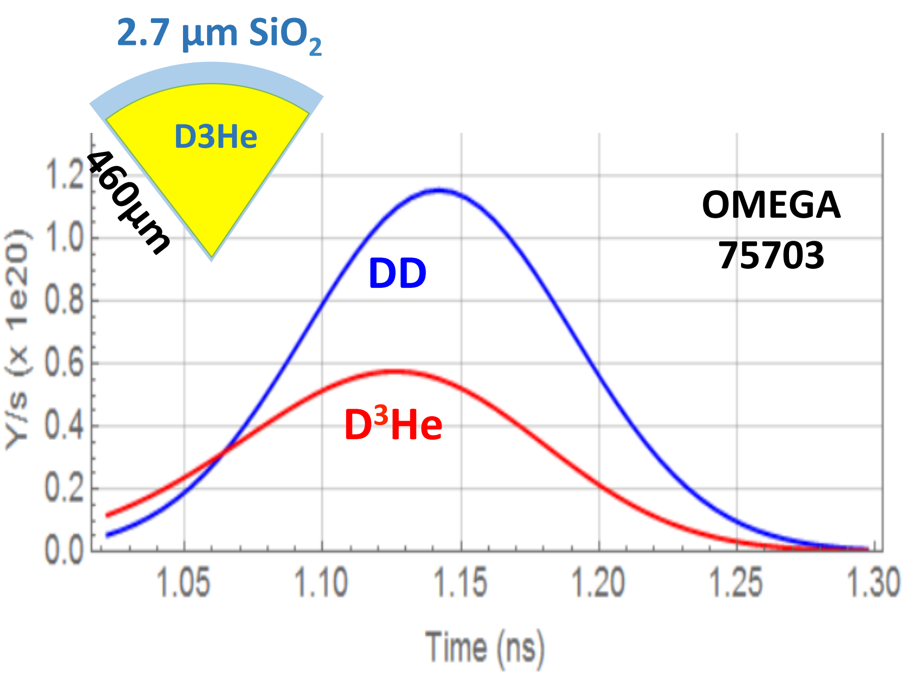
Fundamental Physics experimental proposals

Johan Frenje

High-precision measurements of multiple nuclear burn histories to probe time evolution of species separation in kinetic to hydro-like 1D plasmas

PXTD streak image of DD and D^3He signal





Additional measurements:

- Yield(DD) and Yield(D^3He)
- Tion(DD) and Tion(D^3He)
- Te
- DD and D^3He burn profiles
- R(t)
- Convergence
- ρR_{fuel} and ρR_{tot}
- ….
- ….

Physics motivation:
To quantify the instantaneous rate of species separation in implosions

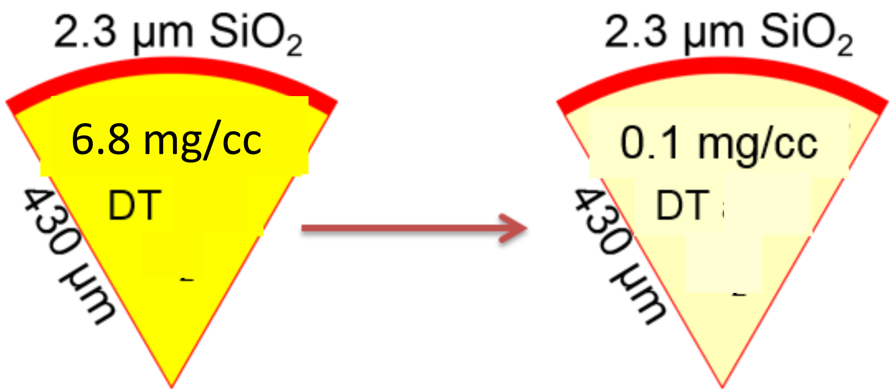
Timescale: Fall 2016

@MIT PSFC

DT exploding pushers at OMEGA will be used to explore the transition between hydro/multi-fluid to kinetic regimes

Hydro regime

Kinetic regime



$\lambda_{ii} << R_{fuel}$
N_K ~0.01
(at bang time)

$\lambda_{ii} >> R_{fuel}$
N_K ~10
(at bang time)

D fraction varied: 20,50, 80, 100%

Measured quantities on one DT shot:

Yield (DD) and Yield (DT): 2 ways
Tion(DD) and Tion(DT): 2 ways
Te
DT and DD burn histories
DT and DD burn profiles
R(t)
Convergence
ρR_{fuel} and ρR_{shell}
....
....

PHYSICS MOTIVATION:
Simplest possible implosions with extensive precision diagnostics, **leaving no wiggle room**, that can be compared in detail to fluid, hybrid, and kinetic simulations.

RELEVANCE:, hot-spot ignition with DT (shock convergence), wetted foam, shock ignition, species separation, species temperature disequilibrium, tau (e-i), ...

Juan Fernandez

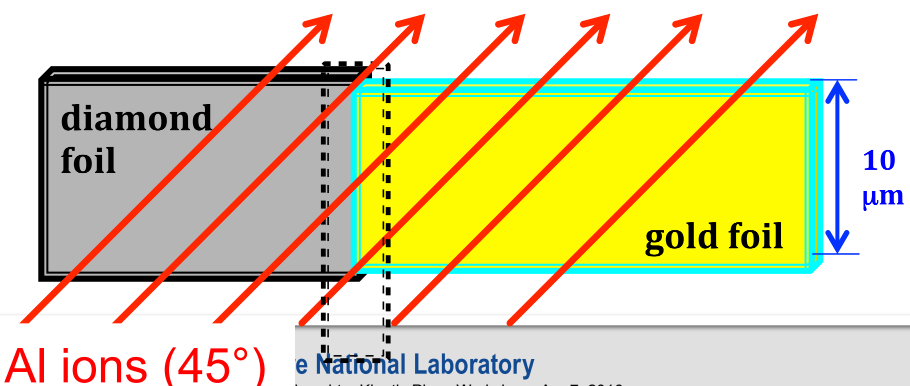
Theoretical and Experimental Investigation of Plasma Mix Across Heterogeneous Interfaces

Timescale: 1-2 yr
EP? Long duration?

Typical model problem: initially sharp, solid density, stationary, 1D interface with high-Z/ low-Z species.

Even in such a “simple" system, without any hydrodynamics drive, different models typically give different results for how the plasmas mix. Such plasmas can mix faster than single fluids by a variety of processes, ranging from ambipolar diffusion to "super diffusion" rooted in kinetic effects. At LANL, versions of this problem are being modeled with RAGE, 2-fluid, VPIC, iFP, MOD-MD codes.

The problem is of practical importance in ICF because plasma mix may determine the initial “perturbation” for hydrodynamic instability, affecting capsule performance. That initial “perturbation” may match, and even exceed other traditional sources (surface roughness, drive asymmetry, stalks and tents, etc.)



Ongoing Expt’s at LANL Trident laser: a “unit physics” experiment involving rapid isochoric heating of a sharp interface.

- Intense laser-driven ion beams heat the interface as isochorically as possible.
- Geometrically simple configuration (free of competing effects).

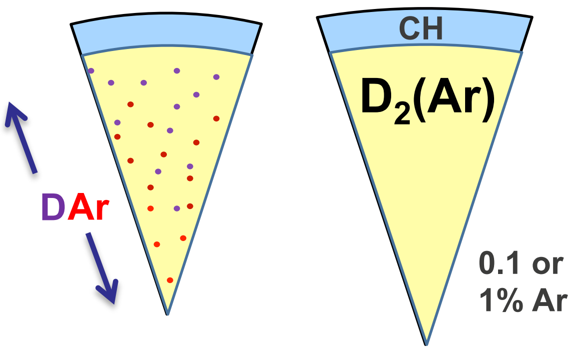
Current goal: establish whether predicted kinetic effects are present.

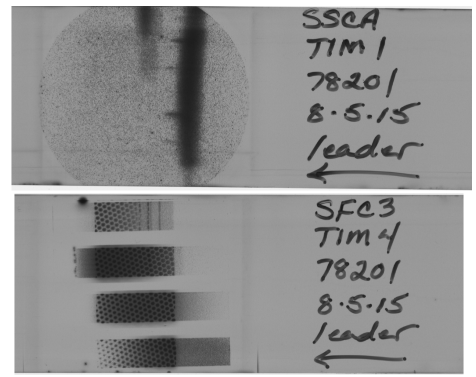
Next steps:

- validate interface diffusion effects as quantitatively as possible.
- Develop reduced models to include in lower-fidelity 1-fluid design codes.

Proposal: continue characterization of ion species separation via x-ray spectroscopy based on the IonSepMMI concept

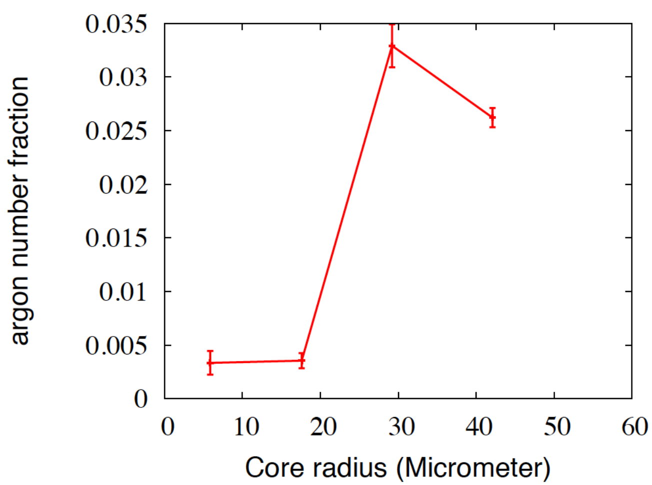
Scan hydro – kinetic +nuclear





Streaked x-ray spectrum (from SSCA)

Multi-monochromatic imager (MMI) data



- **New campaigns should/could pursue:**
  - Explore wider parameter space (different shell thickness, fills, argon concentrations) from kinetic to diffusive regimes
  - Add 3rd MMI to better assess 2D/3D effects on the x-ray-spectroscopy analysis
  - Combine with reaction-history-type diagnostics
  - Dope the shell with titanium to assess the effect of shell mix on the data analysis
  - ??

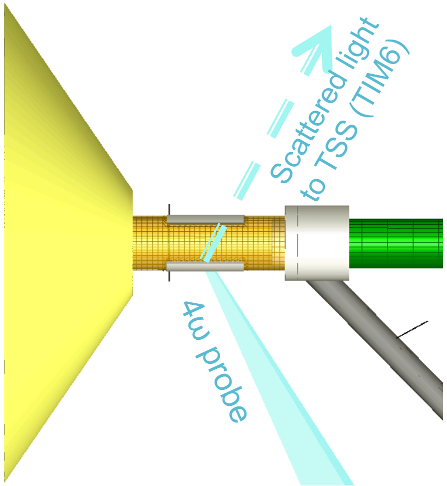
Slide submitted by Scott Hsu, LANL for LLNL Kinetic Effects Workshop

Hans Rinderknecht (Yuan Ping, similar)

Shock-front structure can be measured in single- and multi-ion species plasmas, using Thomson scattering and p+ radiography

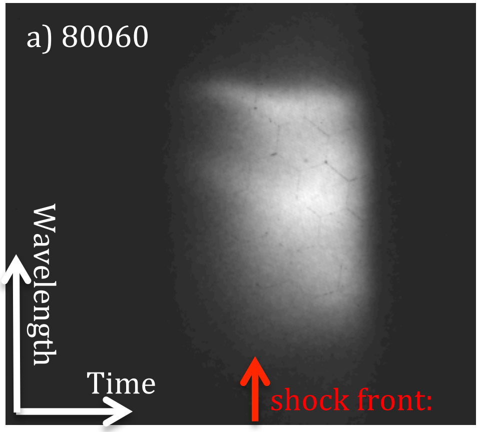
Three-species
Varying Z/A, etc. (kp, kE, kT…)
Timescale: July 2016

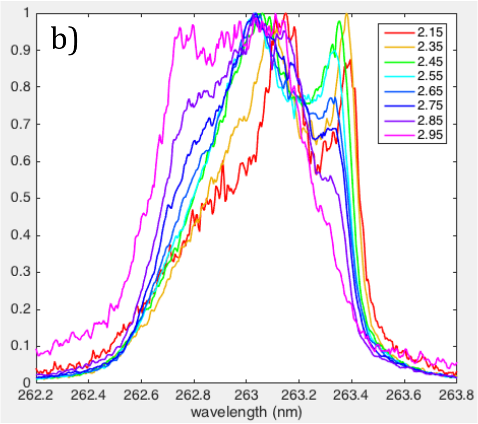
Shock-tube design:



Low-density-gas filled shock-tubes on OMEGA demonstrated with shock Δx (~1mm) >> TS spot (160 um)

Preliminary TS data from H(98%)Ne(2%) shock:





Shock-front structure is an *intrinsically kinetic* phenomenon:

- shock width Δx = 30-70 λ_{ii}
- Strong E-fields (GV/m)
- Ubiquitous in ICF designs, esp. in DT vapor (N_K>0.1)

Methods:

- Proton radiography to measure E-field structure at shock front (Hui, Li)
- Optical Thomson scattering (TS) to measure time & space-resolved n_e, "T_e", "T_i", v_{fluid} and ion composition.

Proposed Experimental studies:

- Single- and multi-ion shock structure
- Vary Mach #, λ_{ii}, gas composition, pre-shock conditions

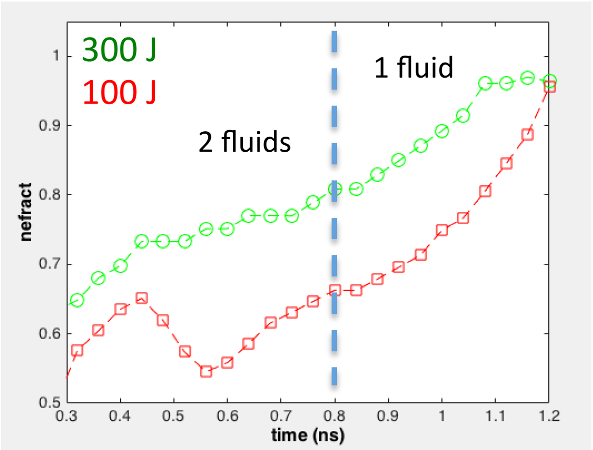
Study of multifluids to single fluid transition on Omega

Sebastien LePape
Laurent Divol

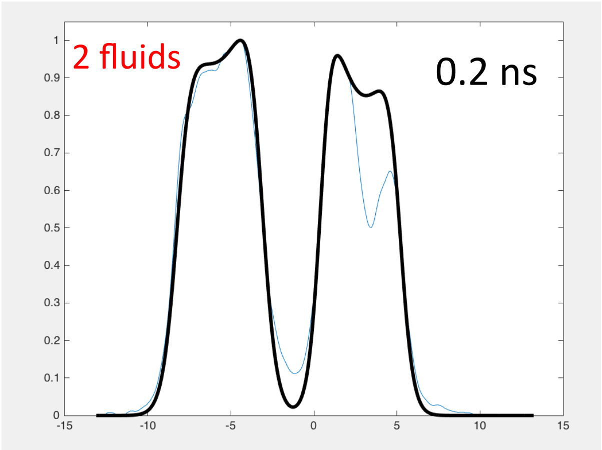
On Omega, using OTS, we have observed a transition from 2 fluids to a single fluid and measured species fraction, Ti, Te, Ne in the TS volume.

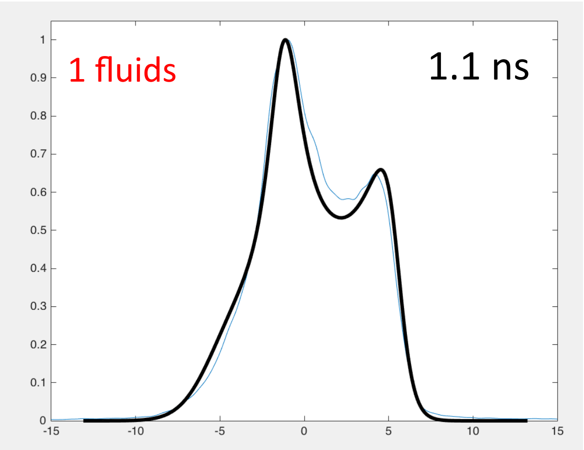
Data exists.
Shots next year

Fraction of electron density coming from ring material



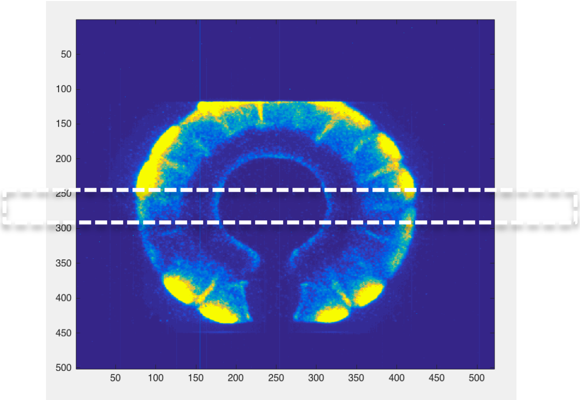
IAW spectrum for 100 J C-C shot





Proposal for follow up experiments on the study of gold/helium/carbon interpenetration in hohlraum

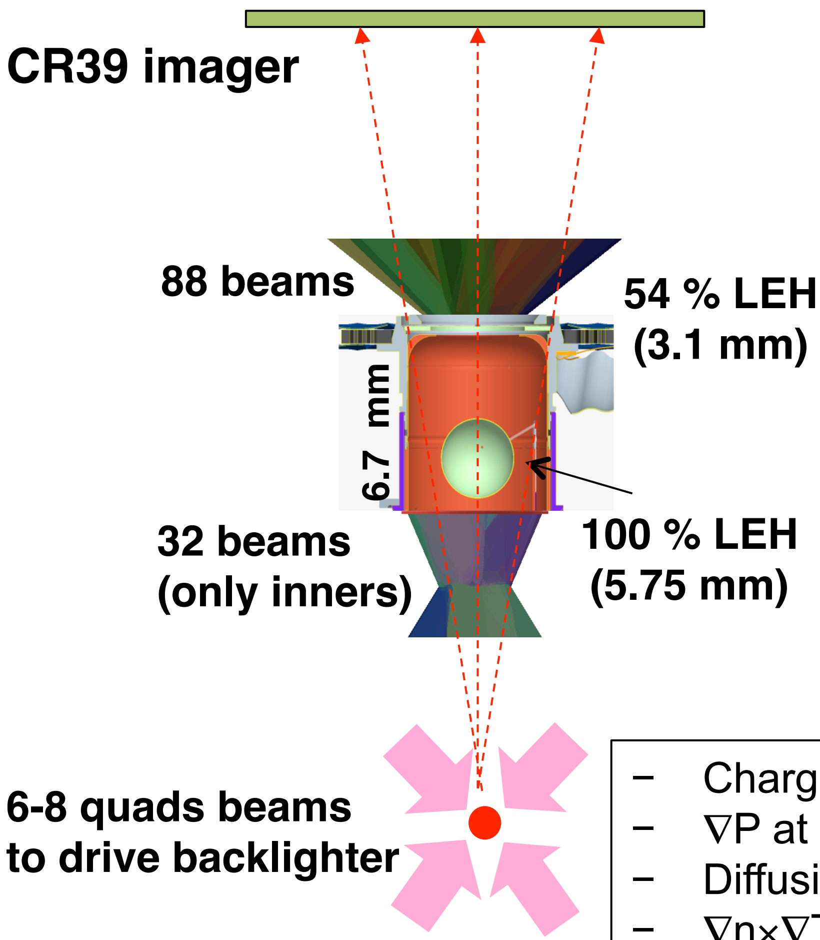
- 1D Thomson scattering imaging along the target radius
- Asses the effect of helium on the interpenetration
- Test the effect of foam on the interpenetration
- Vary pointing geometry (RT instabilities)
- Combine with proton radiography to image associated fields

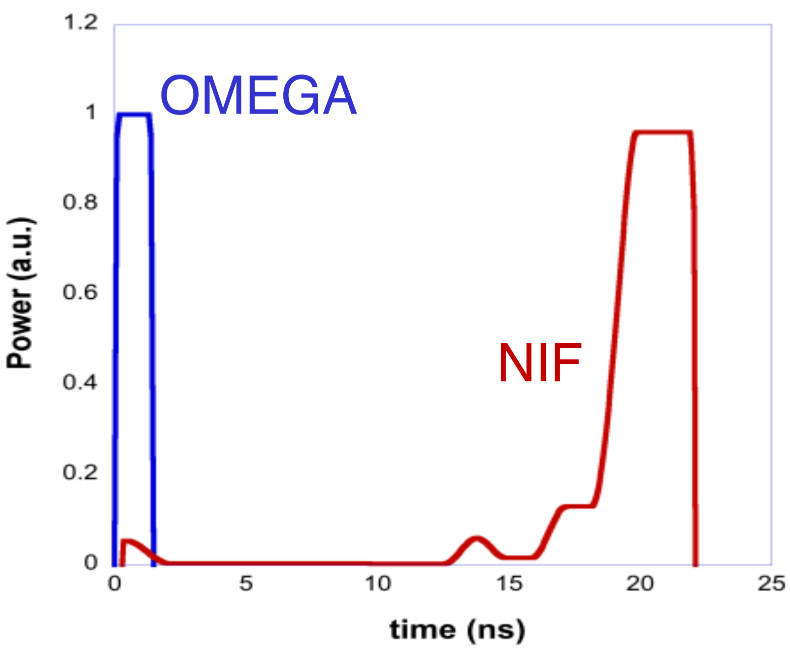


Integrated Scaling Studies proposals

Chikang Li

We expect that proton radiography will measure self-generated fields and their effects on NIF experiments, providing insight into ICF hohlraum dynamics

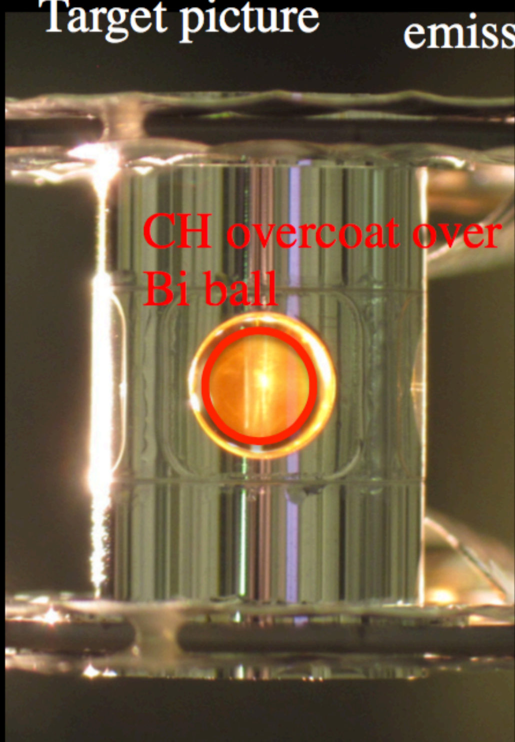


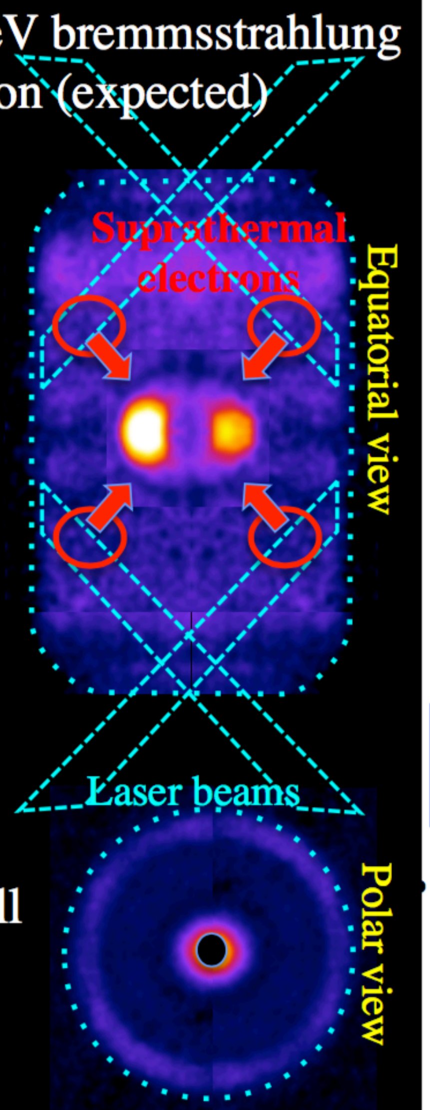


- Charge sheath formed by Ponderomotive force → E fields
- ∇P at hohlraum wall → E fields
- Diffusive mix at interfaces → ambipolar E fields
- $\nabla n \times \nabla T$ around laser spots → B fields
- Hydro unstable interfaces → RT induced B fields

Image emission from hot electrons created during the rise of the main laser pulse, using a capsule surrogate (CH-coated, high-Z sphere) – based on picket study (E. Dewald, PRL 2016)

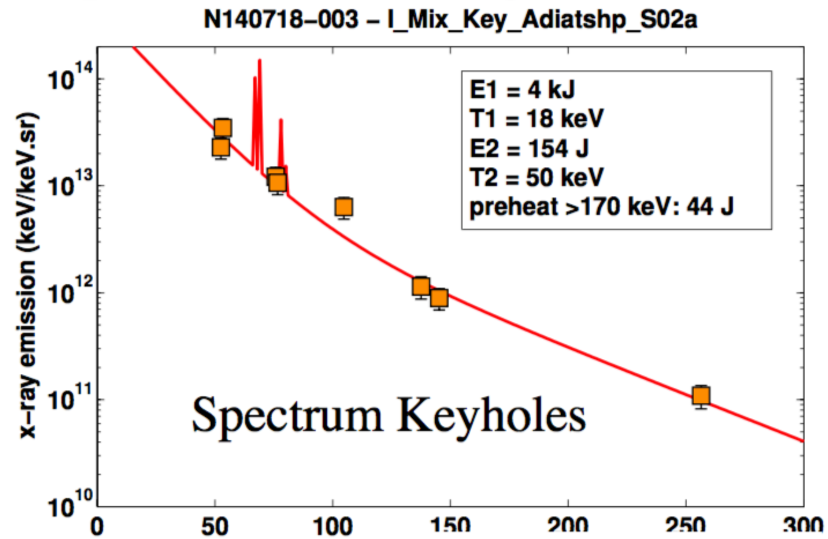
Bedros Afeyan
E. Dewald
Polymath Research Inc.

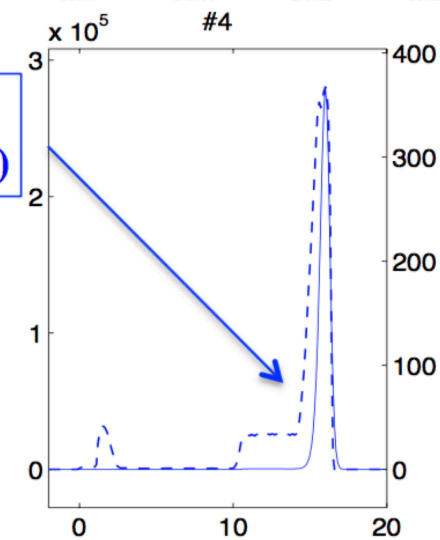




- Improved resolution will be achieved (~100 um) due to higher hot-e amount

20-40x more hots are expected than in the picket for HiFoot, high fill cond.

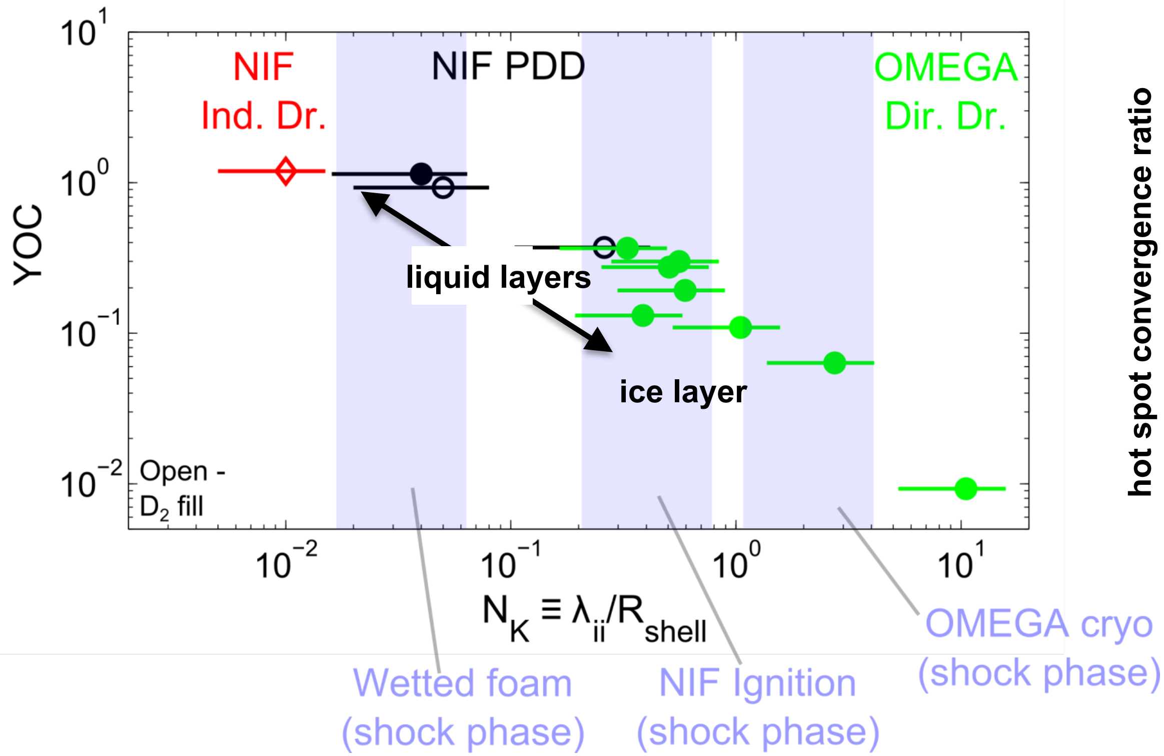


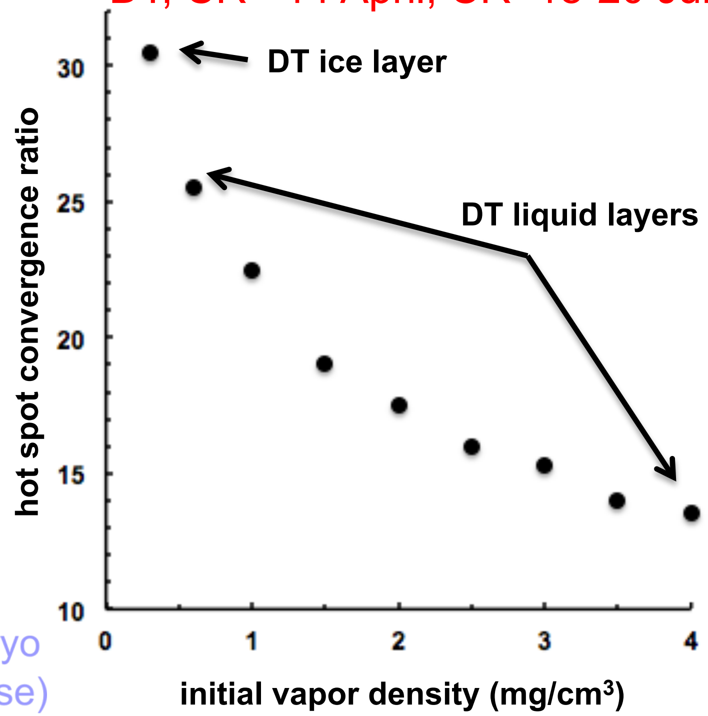


- Overcoat (<20% of initial mass) works since capsule does not implode much in the rise

Liquid layer capsules might be useful for exploring the transition from "hydro-like" to "kinetic-like" behaviors at the time of shock convergence.

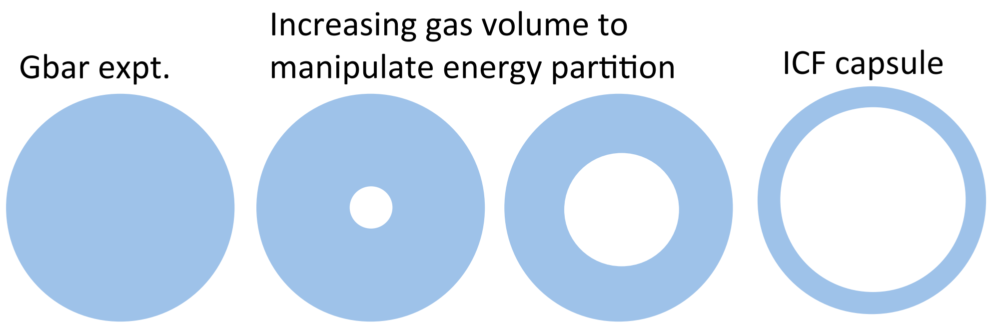
Timescale: platform development
DT, CR =14 April; CR=18-20 June





Yuan Ping, Jim Gaffney, Ryan Rygg

"DT Gigabar" platform for hotspot formation dynamics



Scaling of transport phenomena:

- L^3 ~ Radiation, e-i equilibr., fusion
- L^2 ~ Conduction
- L ~ Knudsen #, particle stopping

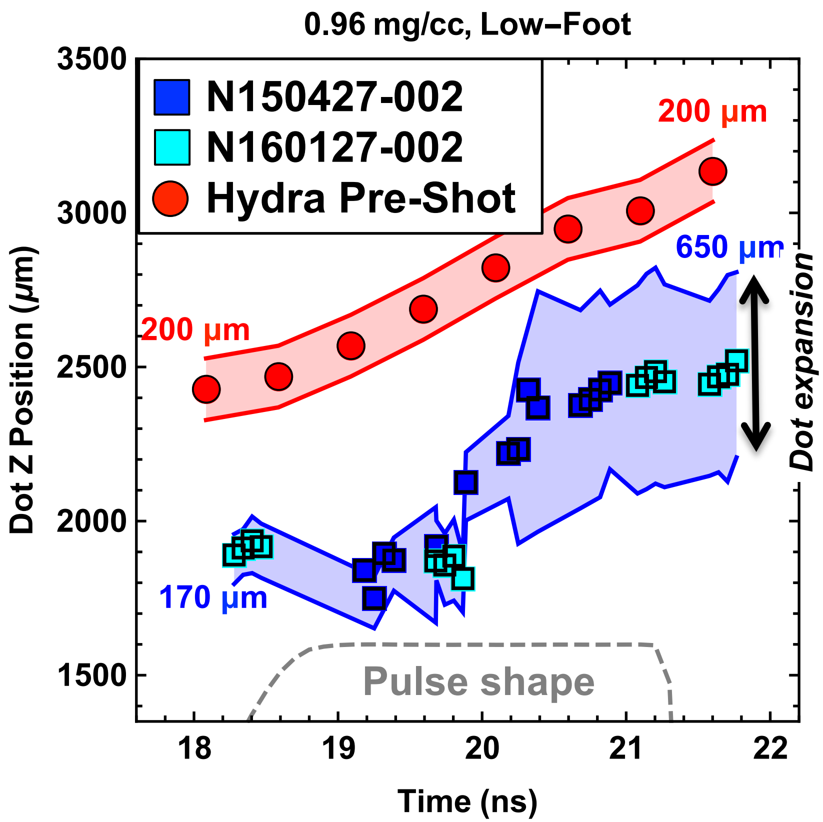
We propose to perform a series of scaling experiments to manipulate various energy losses using convergent geometry, bridging the gap between focused benchmarking experiments and integrated campaigns.

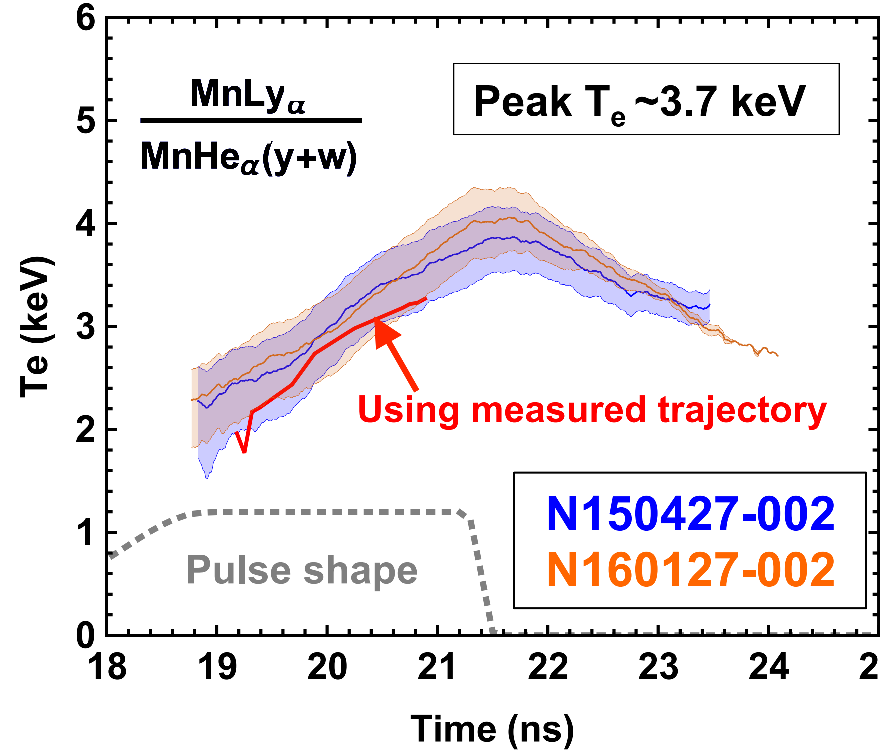
We will start with simple design such as a solid ball in the Gbar platform, and then systematically increasing the gas volume inside the ball.

Because the energy transport processes have different dependence on the scale length or volume, the relative dominance of these processes can be manipulated by varying the hot spot size.

Maria Barrios

Hohlraum interior conditions are being probed using "dot spectroscopy" – constrain models of Te, interpenetration.





Hydra Pre-Shot Simulation uses Flux limiter = 0.15, no-inline SRS, SBS removed, no drive multipliers

Proposed simulation & theory efforts

Code Verification:

- Shock separation analytical test case (Hoffman)
- Timeline for iFP development (Taitano)
- Several more…

Theory efforts:

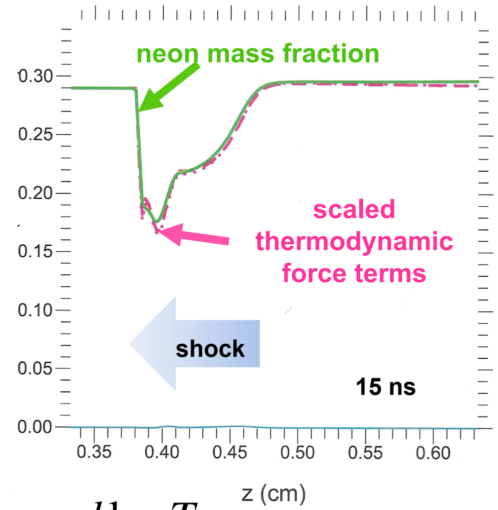
- Evaluate physics of ablator phase transition (Orth)

Nels Hoffman

Species separation in planar steady shock wave replicates thermodynamic force terms, if Péclet number is large

- **Planar steady shock wave in binary mixture**
- **Solution to continuity equation for mass fraction c of light species**

$$c(x) \cong c_+ + \frac{F(x)L_i}{R_+(x)Pe(x)} - \sum_{n=1}^{\infty} \frac{L_i^{n+1}}{\left[-R_+(x)Pe(x)\right]^{n+1}} \frac{d^n F(x)}{dx^n}$$



where

c_+ **= mass fraction in unshocked material**

$F(x)$ **is thermodynamic force:**

$$F(x) = k_P(c(x))\frac{d\log P_i}{dx} + k_E(c(x))\frac{T_e}{T_i}\frac{d\log \rho}{dx} + k_T^{(i)}(c(x))\frac{d\log T_i}{dx} + k_T^{(e)}(c(x))\frac{d\log T_e}{dx}$$

$Pe(x)$ **is Péclet number:** $Pe(x) = u_+L_i/D(x)$, **where** u_+ **is shock velocity,** L_i **is shock width,** $D(x)$ **is diffusivity,** $R_+(x)$ **is (compression)$^{-1}$ =** $\rho_+/\rho(x)$

- **When Pe is large,** $$c(x) \approx c_+ + \frac{F(x)L_i}{R_+(x)Pe(x)}$$

Expression is suggested by solution to approximate linear ODE with constant coefficients

Timeline for development and application of iFP

- **2016**
  - **Code development/improvement (~mid summer to fall)**
    - Improved shock tracking moving mesh capability
  - Verification
    - Spherical shock verification problems
    - Fluid electron model with grad(Te)
- **2017 (considerable uncertainty past this point!)**
  - **Code development**
    - Burn diagnostics
    - Grid adaptivity based on drift velocity (depends on demand and physics interest)
    - Radiation transport model (depends on demand and physics interest)
  - Verification
    - Moving radial mesh verification
    - Comparison against FPION simulations
- **2018**
  - Code development;
    - Kinetic electrons
    - Kinetic alphas
  - Verification
    - Alpha slowing down

What does this look like in existing OHRV data?
X-ray diffraction on LCLS to evaluate state?
(req. Mbar)

C. Orth preliminary proposal — Add phase nucleation & spallation to target design codes

- When a ≥1 Mbar-level shock transits ablator material still in a solid phase (e.g., as determined by its temperature or MJ/kg), keep it in the solid phase for another Δt ps (e.g., don't let it expand). — This is secondary.
  - Work with Orth to determine Δt (~200 ps?).

- If the shock transit of a solid region is adjacent to the fuel, make the solid spall according to the following reference, delay the shock propagating further by Δt ps, and roughen the surface according to the expected size of the spalled chunks (1, 10, and 14 microns respectively for HDC, sintered Be, and GDP-CH).
  - This is primary (and not easy).
  - C. Orth, Physics of Plasmas, **23**, 022706-1 (2016).

04/07/2016